

EVOLUTION OF DISK GALAXIES IN THE GOODS-SOUTH FIELD: NUMBER DENSITIES AND SIZE DISTRIBUTION.¹

S. RAVINDRANATH², H. C. FERGUSON^{2,3}, C. CONSELICE⁴, M. GIavalisco², M. DICKINSON^{2,3}, E. CHATZICHRISTOU⁵, D. DE MELLO⁶, S. M. FALL², J. P. GARDNER⁶, N. A. GROGIN³, A. HORNSCHEMEIER³, S. JOGEE², A. KOEKEMOER², C. KRETCHMER³, M. LIVIO², B. MOBASHER², R. SOMERVILLE²

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ABSTRACT

We examine the evolution of the sizes and number densities of disk galaxies using the high resolution images obtained by the Great Observatories Origins Deep Survey (GOODS) with the Advanced Camera for Surveys (ACS) on the *Hubble Space Telescope* (*HST*). The multiwavelength images are used to classify galaxies based on their rest-frame *B*-band morphologies out to redshift $z \sim 1.25$. In order to minimize the effect of selection biases, we confine our analysis to galaxies which occupy the region of magnitude-size plane where the survey is $\sim 90\%$ complete at all redshifts. The observed size distribution is consistent with a log-normal distribution as seen for the disk galaxies in the local Universe and does not show any significant evolution over the redshift range $0.25 \leq z \leq 1.25$. We find that the number densities of disk galaxies remains fairly constant over this redshift range, although a modest evolution by a factor of four may be possible within the 2σ uncertainties.

Subject headings: galaxies: evolution — galaxies: formation — galaxies: fundamental parameters — galaxies: structure

1. INTRODUCTION

Disk galaxies constitute about 60–80% of the galaxies in the nearby Universe (Buta et al. 1994) and it is very important to understand how they formed and evolved. In the recent years, high resolution images from *HST* have proved extremely valuable in obtaining the structural parameters of galaxies out to $z \sim 1$. In this letter, we address the issue of whether the size distribution and number density of disk-dominated galaxies evolves with redshift. The evolution of disk galaxies has been explored previously via the magnitude–size ($M_B - r_e$) relation (Schade et al. 1996; Lilly et al. 1998; Roche et al. 1998; Simard et al. 1999); Bouwens & Silk, 2002) and the Tully-Fisher ($M_B - V_c$) relation (Vogt et al. 1996). Based on *HST* imaging, most studies found evidence for a significant increase (~ 1 –1.3 magnitude) in the rest-frame *B*-band surface brightness of disk galaxies to $z = 1$, while Simard et al. (1999) found no evidence for surface brightness evolution once the selection effects of the survey were taken into account. The luminosity–size evolution of disks remains a controversial issue and the interpretation of any observed evolution with redshift depends crucially on accounting for the selection biases of the survey (Simard et al. 1999; Bouwens & Silk, 2002). Lilly et al. (1998) reported that the abundance and size distribution remains constant out to $z \sim 1$, for the large disks with scalelengths greater than ~ 5 kpc, for which their sample is fairly complete. The space densities at different look-back times provides a key observable to help determine how and when large galaxies like the Milky Way were formed.

The multi-wavelength (B, V, i, z) *HST/ACS* images from GOODS serve as an excellent resource to examine the size

and number density evolution of disk galaxies with redshift. The availability of a long wavelength baseline from 4300Å to 9000Å allows galaxy properties to be studied consistently in the rest-frame *B*-band for galaxies out to $z \sim 1.25$. Also, the large area of the survey provides an ample number of galaxies over the range $0.25 \leq z \leq 1.25$ for studying the number density evolution. We adopt the cosmology defined by $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\lambda = 0.7$ throughout this paper.

2. MORPHOLOGICAL ANALYSIS AND IDENTIFICATION OF DISKS

The analysis presented here is based on the first three epochs of observations of the Chandra Deep Field South (CDF-S) obtained via the GOODS program. The sample consists of all sources from the SExtractor (Bertin & Arnouts 1996) source catalogs of the GOODS CDF-S region (Giavalisco et al. 2004) with $z_{850} \leq 24.0$ magnitude⁷ and stellarity index < 0.8 . These criteria ensure that the signal-to-noise ratio is sufficient for the morphological analysis and excludes the stars. The photometric redshifts for the galaxies are from Mobasher et al. (2004) and are found to be robust ($rms \leq 0.11$) out to $z \sim 1$ for objects with $z_{850} \leq 24.0$ magnitude based on the comparison with available spectroscopic redshifts. The final sample consists of 2781 objects with $0.25 \leq z \leq 1.25$.

We derive the structural parameters of the galaxies through a two-dimensional modelling of the surface brightness distribution using the GALFIT software (Peng et al. 2002). We use a single Sérsic (Sérsic 1968) function to model the brightness profiles, and used simulations to verify that the Sérsic index, n , can provide a reliable classification of the bulge-dominated and disk-dominated galaxies even at the faint magnitudes. The

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² The Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218.

³ Department of Physics and Astronomy, The Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218

⁴ California Institute of Technology, Mail Code 105–24, Pasadena, CA 91125

⁵ Department of Astronomy, Yale University, PO Box 208101, New Haven, CT 06520

⁶ Laboratory for Astronomy and Solar physics, Code 681, Goddard Space Flight Center, Greenbelt, MD 20771

⁷ z_{850} denotes observed AB magnitude in the F850LP filter. The limiting isophote for the source detection was ~ 27.3 magnitude/arcsec² in the *z*-band.

quality of the best-fit model is judged based on the reduced chi square (χ^2_ν) value which should be close to unity when the model is a good match to the data.

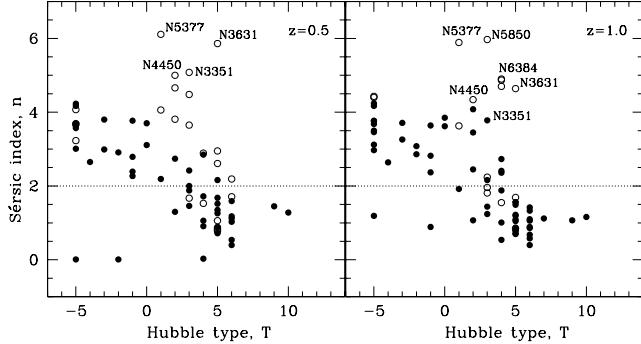


FIG. 1.— The measured Sérsic index versus galaxy Hubble type from RC3 (de Vaucouleurs et al. 1991), for the redshifted Frei sample. Disk galaxies are found to have $n < 2.0$ and bulges have $n > 2.0$. The open circles represent galaxies which have low surface brightness, and constitute most of the outliers in our classification scheme. The galaxies that deviate most from their expected galaxy type are labelled, and in most cases have a bright nucleus or star-forming regions which complicates the fits. Objects with $n = 0$ have large χ^2_ν values because the fits were poor.

The index, n , is known to correlate with galaxy morphology (Andredakis, Peletier, & Balcells 1995). In Figure 1, we illustrate the classification based on n , using nearby galaxies from the Frei sample (Frei et al. 1996), which have been redshifted artificially to $z = 0.5$ and $z = 1.0$ (Conselice 2003). The criterion $n < 2.0$ allows us to select disk-dominated galaxies (Sbc-Sdm) even when they have morphological complexities such as dust, star-forming regions, etc. However, a few late-type galaxies have high n due to the presence of a bright nucleus, or circum-nuclear star formation in the center and may be missed by our disk selection criterion. It is encouraging that only few early-type galaxies migrate to the low n values, and they usually have large χ^2_ν values which implies poor fit to the data.

The structural parameters for the galaxies were measured in the rest-frame B -band at all redshifts. When the rest-frame B -band is redshifted to wavelengths that fall in the gap between two filters, we use an average of the measurements made in the two filters. We identified 1508 disk galaxies, after excluding about 1% of the galaxies with $n < 2$ that have $\chi^2_\nu > 5$. Based on the spectral type used to assign photometric redshifts, we estimate about 3% contamination from ellipticals and S0's within our sample of disk galaxies. We adopt the effective (or half-light) radius, r_e , from the Sérsic fit as a size measure. Errors on the measured sizes and magnitudes were estimated using extensive simulations done by introducing “artificial” galaxies with exponential disks and $r^{1/4}$ bulges into the GOODS images (Giavalisco et al. 2004). The simulated galaxies have bulge-to-disk (B/D) ratios covering the range $-0.6 < \log(B/D) < -1.8$ typical of Hubble types Sa to Sdm (Graham 2001), disk magnitudes $18 \leq z_{850} \leq 24$, disk half-light radii $0''.1 \leq r_e \leq 3''.0$, and various ellipticities and position angles. We find that the systems with $n < 2$ are predominantly galaxies with $B/D < 0.1$ and the bulge does not influence their derived disk parameters significantly. For galaxies with $n < 2$, the mean difference in the integrated magnitudes and half-light radii between the recovered values using the Sérsic profile and the input disk parameters was $<\Delta z_{850}> = -0.14$ mag and $<\Delta \log r_e> = 0.06$ with dispersions of $\sigma \Delta z_{850} = 0.40$ and $\sigma \Delta \log r_e = 0.08$.

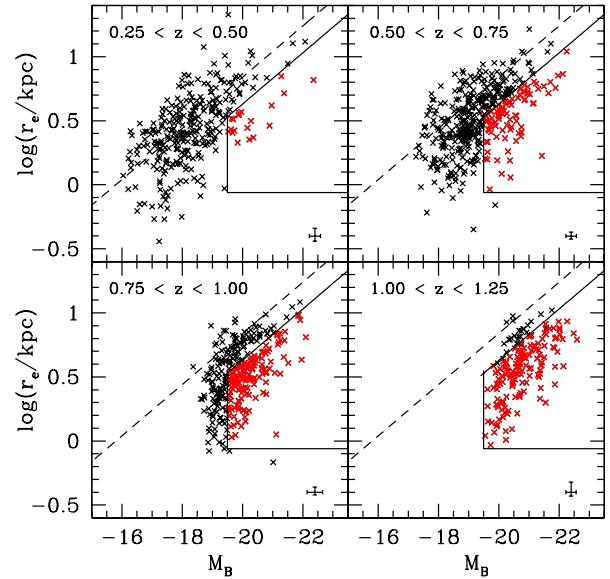


FIG. 2.— The absolute B magnitude versus half-light radius ($M_B - r_e$) relation is shown for all the observed disk galaxies as a function of redshift. The trapezoidal region (solid line) is bounded by $M_B = -19.5$, $r_e = 0.8$ kpc, and $\mu_B^0 = 20.6$ mag arcsec $^{-2}$, and encloses the disk galaxies that are least affected by selection biases (red crosses) at all redshifts. In each panel, representative error bars are provided for a galaxy with median properties of the “selection-free” sample. The dashed line shows the Freeman relation for exponential disks with constant central surface brightness, $\mu_B^0 = 21.65$ mag arcsec $^{-2}$.

3. RESULTS

Magnitude–size relation for disk galaxies: In order to compare the evolution of disks at different redshifts it is important to consider the effect of selection biases which can artificially introduce evolutionary signatures in the absolute magnitude–size ($M_B - r_e$) plane shown in Figure 2. From our simulations we found that the selection in the z -band is more than 90% complete for disk galaxies with surface brightness, $\mu_z^e \leq 23.4$ mag arcsec $^{-2}$, measured within the effective radius. Assuming an exponential profile for the disks, this corresponds to a rest-frame B -band central surface brightness of $\mu_B^0 \leq 20.6$ mag arcsec $^{-2}$ in the highest redshift bin. The $z_{850} \leq 24$ magnitude criterion adopted in the sample selection translates to $M_B \leq -19.5$ in this redshift bin, and the smallest disk size is $r_e \sim 0.8$ kpc. Thus, disk galaxies with $M_B < -19.5$, $\mu_B^0 \leq 20.6$ mag arcsec $^{-2}$, and $r_e > 0.8$ kpc are almost free of selection biases at all redshifts and their distribution in the $M_B - r_e$ plane must reflect the actual luminosity or size evolution. Therefore, only disk galaxies satisfying the above criteria (red points in Figure 2) are considered for further analysis. At redshifts $z \geq 1$, the surface brightness threshold for 90% completeness is about a magnitude brighter than the Freeman value. The small number of disks with luminosities $M_B < -21$ in the lowest redshift bin is striking even after accounting for the difference in co-moving volumes in the various redshift bins. There is a class of high surface brightness disks with $M_B < -21.5$ and $r_e < 4$ kpc which become dominant at $z \geq 1$; a similar observation of high surface brightness disks at $z \geq 0.9$ was also reported by Simard et al. (1999). These objects could be among the most strongly evolving disk population from $z \sim 1$ to the present.

In Figure 3 the luminosity function (LF) is presented for the “selection -free” disk galaxies in all redshift bins along with

a representative “non-evolving” LF⁸. Our selection criteria restricts the analysis to the most luminous disks and the observed LF at $z < 1$ is well-represented by a non-evolving LF over the range of luminosities considered. However, at $z > 1$, the number of luminous disks with $M_B < -21$ is marginally higher than expected from the non-evolving LF and the observed points show a relative shift towards higher luminosities.

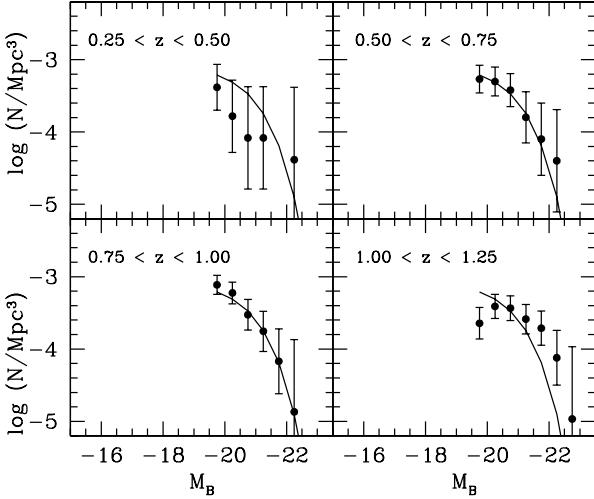


FIG. 3.— The observed LF (filled circles) for disk galaxies chosen to be **free of selection biases** from figure 2, is presented along with the Poisson error bars. A non-evolving LF (solid line) similar to that observed for local spiral disks (de Jong & lacey 2000) is also shown and is characterized by $M_B^* = -20.6$, $\alpha = -0.90$. The normalization adopted for the non-evolving LF has been adjusted to match the total number of galaxies at $0.50 \leq z \leq 0.70$ and is held fixed for the other redshift intervals to look for evolutionary signatures within the sample.

Size distribution of disk galaxies: Overall, the size distribution (SD) for disk galaxies is consistent with a log-normal distribution and there is no noticeable size evolution with redshift within our sample (Figure 4). To examine the effect of the selection and the measurement biases on the observed SD at various redshifts within the sample, we carried out simulations by inserting “artificial” disk galaxies in the GOODS images (see §2). The disk galaxies in the local Universe show a log-normal size distribution, and luminosity-size relation, $r_e \propto L^{-\beta} \sim L^{1/3}$ (de Jong & Lacey 2000). We adopt this analytical form and the LF discussed in the previous section, for the input non-evolving luminosity-size distribution function for galaxies in our simulations. After applying the same selection function to the simulated galaxies as done for observed galaxies, the sizes are re-measured for the “selection free” sample. At all redshifts, the surface brightness threshold adopted for the selection affects the SD at large radii, and the peak of the distribution shifts to smaller sizes. The measured sizes are in good agreement with the input sizes in the simulations for $z < 1.00$, but are biased towards larger sizes at higher redshifts. For the non-evolving model this occurs because galaxies become increasingly fainter at high redshifts and the uncertainties in the background estimation are larger. Thus, for the observed galaxies the SD is not significantly affected by the selection or measurement bias for small disk sizes ($r_e < 4$ kpc) at $z < 1$. But at higher redshifts, given the nature of the measurement bias an evolution in the SD

due to the small disks cannot be distinguished from the effect of luminosity evolution which can make disks brighter and reduce the bias.

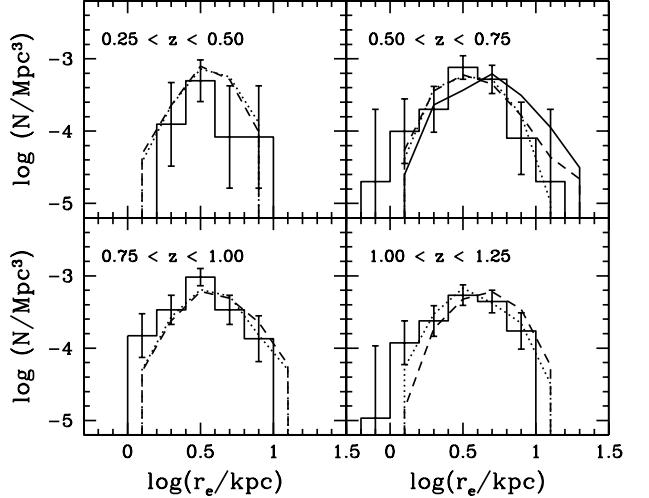


FIG. 4.— The histogram shows the observed size distribution along with the Poisson error bars for the disk galaxies which are **free of selection biases**. The curves show the effect of selection *dotted line* and measurement *dashed line* on an input “non-evolving” SD *solid line* based on simulations. The input log-normal distribution (prior to selection and measurement) with a peak at $r_e = 6$ kpc and width $\sigma(\ln r_e) \sim 0.5$ provides a good match to the size distribution observed at $0.50 < z < 0.75$ after the selection criteria is applied, and is held fixed for the other redshifts; the normalization has been adjusted to match the number of galaxies in this redshift bin. The selection causes the peak of the log-normal distribution to shift to smaller sizes ($r_e = 4$ kpc). Measurement biases are significant only in the highest redshift bin.

Number densities of disk galaxies: The observed number density of disk galaxies (Figure 5) that are free of selection biases in the GOODS CDF-S field, is found to remain almost unchanged out to redshift of $z = 1.25$ within the uncertainties. We divided the sample into small disks ($r_e < 4$ kpc) and large disks ($r_e \geq 4$ kpc) to look for differences in their relative abundances. Neither sample shows strong evolution within the uncertainties, except for a mild increase in the number of small disks at $z \sim 0.8$. Assuming that the evolution in number density can be expressed in the form, $n(z) \propto (1+z)^\alpha$, a formal linear regression analysis gives $\alpha = 0.08 \pm 0.23$ for all disks, and $\alpha = 0.00 \pm 0.27$ and 0.20 ± 0.39 for the small and large disks respectively. In all cases, the best fit favors an almost constant number density over the whole redshift range. However, a factor of four change in the number densities of small disks cannot be ruled out within the 2σ uncertainties of the obtained fits. The same is true for the large disks if we exclude the lowest redshift bin where the uncertainty is large. Thus, ignoring the possible effects of luminosity evolution at $z > 1$, it appears that the population of disk galaxies could have undergone only very modest evolution in their number densities from $z = 0.25$ to $z = 1.25$. In order to check for contamination from bulge-dominated galaxies that scatter into the sample at faint magnitudes we re-did the analysis using only those galaxies with $n \leq 1.5$, which have negligible bulge component and obtained very similar results.

⁸ Although a direct comparison with LF of disk galaxies at $z = 0$ (de Jong & Lacey 2000) would be ideal, the difference in the sample selection makes such a comparison non-trivial and we defer such a comparison to a future paper. For simplicity, we adopt the same functional form for the model “non-evolving” LF to facilitate a comparison within the GOODS data set.

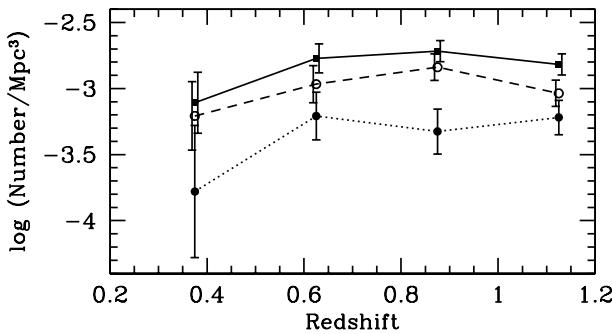


FIG. 5.— The observed number densities of all disk galaxies (filled squares, solid line) within the “selection free” region in Figure 2, is shown as a function of redshift along with the statistical errors. The number densities of small disks ($r_e < 4$ kpc, open circles, dashed lines) and large disks ($r_e \geq 4$ kpc, filled circles, dotted lines) do not show significant evolution in their relative abundance with redshift.

4. DISCUSSION

In the context of evolution of disk galaxies in the $M_B - r_e$ plane, it is important to investigate the effects of B -band surface brightness increase by $\sim 1.1\text{--}1.5$ mag out to $z \sim 1$, claimed by some studies and contradicted by others (see §1). To allow direct comparisons at different redshifts within the GOODS data, we confined our analysis to galaxies with $M_B < -19.5$ and $\mu_B^0 < 20.6$ mag arcsec $^{-2}$, such that they are not affected by selection biases in any redshift. For this sample, we do not see any significant evolution in the mean B -band surface brightness ($\Delta\mu_B^0 < 0.4$). These results are in agreement with Simard et al. (1999) who apply a uniform selection function from the highest to lowest redshift bins. In contrast, the strong surface brightness evolution seen by Bouwens & Silk (2002) is based on their comparison of samples that span different ranges of luminosity and surface brightness at different redshifts. If we include all the disks in our data within the apparent magnitude and surface-brightness limits for 90% completeness in the z -band, we find an increase in the mean B -band surface brightness by ~ 0.93 mags from $z = 0.2$ to $z = 1$. Such a selection made based on apparent magnitude and size translates to different surface brightness thresholds in the intrinsic $M_B - r_e$ plane at different redshifts. For example, at low redshifts ($z < 0.5$) most of the disk galaxies chosen based on the above criteria have average μ_B^0 close to the Freeman value, while at higher

redshifts the average μ_B^0 for the selected disks shifts to brighter magnitudes. The interpretation of the results in this case would thus depend on comparison to disk evolution models; alternatively a comparison can be made using like samples at different redshifts which is the approach used here.

The size distribution of disks over the redshifts $0.25 < z < 1.00$ is found to remain unchanged and exhibits a log-normal behavior similar to disk galaxies at low redshifts (de Jong & Lacey 2000; Shen et al. 2003). This also agrees with the expectations from the hierarchical models of disk formation (Fall & Efstathiou 1980). However, we note that the observed peak, and shape of the SD at large r_e may be partly affected by the surface brightness threshold (Figure 2) that defines the selection. The evolution of the observed SD at $z > 1$ within the GOODS sample either due to a mild increase in the number of small-sized disks ($r_e < 4$ kpc) or luminosity evolution which makes the disks appear brighter at higher redshifts, cannot be distinguished given the measurement biases. Also, the scatter of bulge-dominated systems into the sample can lead to a similar effect and may pose a challenge to using the simple $n < 2$ criteria for disk galaxy classification at high redshifts.

From the observed number densities and luminosity-size distributions, we conclude that the population of luminous ($M_B < -19.5$), disk galaxies with the sizes ranging from 0.8–10 kpc were present with roughly the same abundance at $z = 1$ as at low redshifts ($z \sim 0.2$) and are likely to have undergone only a modest luminosity evolution. This would require a formation epoch earlier than $z = 1$ for these galaxies. Albeit based on a small number of galaxies, it is interesting that there is evidence for large disks at a mean redshift of $z = 2.3$ (Labbé et al. 2003) with roughly the same abundance as seen for the large disks at $z \sim 1$ in our data. Whether this implies that massive systems like the Milky Way galaxy were already in place at that epoch can be addressed with additional kinematic information to constrain the mass-to-light ratios. A more detailed analysis based on the full GOODS data will be presented in a future paper.

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